# Durability performances of carbon fiber reinforced polymer (CFRP) and concrete bonded systems under moisture conditions

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## ABSTRACT

The information on long-term durability of the carbon fiber reinforced polymer (CFRP)-concrete bond interfaces in various environmental conditions is necessary to predict the service life of the structures. The assessment of the bond interfaces under moisture conditions were evaluated by shear and tension bond tests using 6 popular commercial CFRP and epoxy resin systems in the world for the maximum immersion period of 18 months. The bond tests were also accompanied by the test in the mechanical properties of the resins and concrete. Two of systems showed 25% and 16% reductions in average shear bond strengths, while the remaining systems showed either improvement or a small reduction. Observation of the failure modes suggested that, the durability against water related deterioration are worst when the adhesion bonds between concrete and resin interface are weaker than the cohesive bonds of the adjacent layers. Similarly, the average tensile bond strength reduction was found to

vary from 19% to 41% indicating that the durability of the bond is highly dependent on the CFRP composite systems.

## INTRODUCTION

The strengthening of concrete structural members with fiber reinforced polymer (FRP) is very common and popular recently due to its various advantages over other materials and methods. In spite of wide applicability, the durability information of such materials and the systems under long-term exposure in severe environments are quite limited. In this regard, the environmental deterioration factor currently being proposed by some of the guidelines (ACI-440.2R-08, 2008, CNR-DT-200, 2004) does not extensively cover deteriorations in various environmental conditions under long-term due to insufficient research in the field. Realizing the importance of durability issues in the FRP composites, ACI committee has been developing a guide to accelerated conditioning protocols for durability assessment of internal and external FRP reinforcements for concrete (ACI-440.9R-15, 2015).

During the service life of the structures, some of the common severe environments which can affect the durability of the FRP bonded concrete structures are moisture, high temperature, freeze-thaw cycles, wet-dry cycles, UV radiation, etc. and their synergies. In order to study the above mentioned durability related issues for the FRP bonded concrete structures, researchers around the world have been using accelerated laboratory ageing method with wide variety of testing methods, materials and exposure durations. Due to lack of guidelines to perform such tests and diversity in availability of materials used, there is no uniformity in the results and the degree of its effect. Some of the relevant literatures related to the long-term investigation on durability of FRP-concrete bond under moisture are summarized hereafter.

Karbhari and Ghosh (2009) conducted an experimental study to determine the effects of environmental exposure on durability of bond strength between different commercially available FRP strengthening systems and concrete using direct pull-off test. When 10 different FRP systems were exposed for 2 years, the maximum deterioration was noted for the case of exposure to a sub-zero environment compared to immersion in salt water and deionized water. The authors also suggested that the deterioration of the bond between FRP and the concrete substrate should be considered in the design for rehabilitation measures. Dai, et al. (2010) investigated on the influence of moisture on the tensile and shear bond behavior of FRP to concrete interfaces subjected to accelerated wet-dry cycles (4 days wet at 60˚C and 3 days dry) for the maximum duration of 2 years. The authors reported contradiction in the behavior of tensile and shear bond properties after the exposure. The interfacial bond strength degraded asymptotically with the exposure time, while the flexural capacity of the FRP sheet bonded to concrete beams increased. However, the transition of failure modes occurred in all the cases from concrete cohesion failure to the interface adhesion failure between primers and concrete after the exposure.  Till date, the longest duration of such exposure test was performed by Nishizaki and Kato (2011), in which the durability of bond between carbon fiber reinforcement polymer (CFRP) and concrete through outdoor exposure in a moderate climate for 14 years. The authors evaluated the adhesive bond properties using the pull-off and peel test methods. The pull-off strengths were slightly decreased but the residual values still indicated quite good adhesion properties. In all the cases, failures occurred in the concrete substrate, therefore, the authors pointed out that the reductions observed may not be necessarily related to the degradation of the resin bond properties. In contrast, the results of the peel test showed distinct differences in the failure modes after immersion. Benzarti, et al. (2011) chose 4 different composite systems to perform durability test of adhesive bond between concrete and CFRP under accelerated condition (40˚C and 95% relative humidity) using pull-off test and single lap shear test. After a year of exposure, even though transition of failure mode occurred from cohesive concrete failure to the adhesive interface for most of the cases, the results from the pull-off test were not always consistent with those of the shear test. Significant reductions in the tensile bond strength was observed for most of the systems while there was an increase in shear bond strength. Similarly, Choi, et al. (2012) conducted large experimental program to investigate the effects of various exposure conditions (hygrothermal, outdoor and chloride, alkali and UV/water cycles) on concrete beams externally reinforced with different commercially available CFRP composites. The results showed that the flexural strength of the beam specimens were reduced with exposure, but, significant differences in the relative strength losses were observed in different commercial systems indicating that the durability in such exposures are dependent on the FRP composite system. Based on the strength reduction due to such exposure, the environmental reduction factor which was close to 85% as suggested by ACI-440.2R-08 (2008). Recently, Al-Tamimi, et al. (2014)conducted several single lap shear test on the CFRP precured plates bonded to concrete prisms after being subjected to two marine environment exposures along with the controlled laboratory atmosphere for the comparison. The specimens were preloaded with 3 kN and 5 kN for the period of 150 days before the test. The results indicated that the specimens exposed to the sun and saline environments experienced an increase in the bond strength. The reason for such increase in performance was explained by increase in greater polymer crosslinking of adhesive due to exposure in elevated temperature. All of the above review on the literatures point out that the exposure to moisture condition could be harmful to the FRP-concrete bond interfaces resulting in some reductions in bond strength along with the transition of failure modes, however, the degrees of such effects are vastly dependent on several factors but most importantly the selection of FRP materials along with the epoxy resins.

This paper is the continuation effort of the authors' study on the moisture effect on the FRP-concrete bond interfaces in order to explain different mechanisms and issues associated with long-term degradation of bond. The authors have published some interesting findings of the study in Shrestha, et al. (2014) which include discussion on the results of moisture effect on FRP-concrete bond interfaces using normal and high strength substrate concrete evaluated by single lap shear bond test for the maximum duration of 24 months. The results showed average reduction in bond strength up to 32% and 12% for high-strength and normal-strength concrete substrate respectively. The study also confirmed transition of failure mode from concrete cohesion to mixed failure which is partially at the concrete and partially at primer-concrete interface. But there exists a major limitation of mismatch between exposure and testing conditions (temperature and humidity) in most of the previous studies. The authors figured out that although specimens subjected to water or high humidity at different temperatures, the tests are usually conducted in laboratory environmental conditions. This may affect the bond behavior due to variability of moisture content at the interface as it can change during the setup and testing period as a result of not maintaining the testing conditions. Therefore, it is necessary to maintain the similar exposure condition even during the testing period. The current research program was carried out overcoming such limitation by conducting the test inside high humidity chamber. The long-term durability of 6 commercial CFRP systems bonded to concrete under the influence of moisture exposure and normal temperature were evaluated. This paper contains some interesting results and discussion on effect of moisture on the constituent materials and the bond behavior including various aspects of long-term durability performances of those selected systems which would serve in clarifying the understanding of moisture behavior in CFRP-concrete bonds. The results and findings of the study would also add valuable contribution towards development of durability related guidelines under different environmental conditions in future.

# EXPERIMENTAL PROGRAM

The experimental program includes both material and bond tests. Two types of bond tests, single lap shear test and direct pull-off test were conducted to evaluate the shear and tensile performance of CFRP-concrete interface after different moisture exposure durations, respectively. The material test includes epoxy tension test and concrete compression test by standard coupons and cylinder specimens, respectively.

## Materials description

Altogether 6 commercially available CFRPs and epoxy resins from different regions of the world were selected for the study. The CFRP systems are from the most popular Japanese, European and US based manufactures that include plate, strand sheet and continuous fiber sheets along with their suggested epoxy resins. All of the epoxy resins were room temperature curing resin for standard applications. For two of the CFRP systems, primer layer was used as recommended by the manufacturers before attaching the CFRP sheet onto the concrete surface. Detailed chemical information of the resins and their compositions were not disclosed by the manufacturers, however, some of the general information was extracted from the material safety data sheet (MSDS) of the resins. Based on the information given, primary component of the epoxy curing agents used in the current study is modified polyamine which is either aliphatic polyamine or combination of aliphatic polyamine with cycloaliphatic polyamine. The properties of CFRP reinforcements and the resins are summarized in Table 1.

## Preparation of the specimens

The dog-bone shaped resin specimens for the uniaxial tensile test were prepared following JIS.K.7113 (1995). The specimens were prepared using all the 8 kinds of epoxy resin which include 2 types of primer. The base and hardener was mixed in a recommended proportion and transferred into a vacuum chamber to remove the small air bubbles. The vacuumed resin was then poured into the mold and tapped several times to remove any trapped air from within the specimens. The specimens were cured in an ambient room temperature (Fig. 1) for more than one month before being subjected to any kind of exposures.

Schematic details of the shear bond specimen and direct pull-off specimen are shown in Fig. 2 and Fig. 3 respectively. For the preparation of bond specimens, concrete prisms were roughened with a disk grinder conforming to concrete surface profile (CSP) of level 4, cleaned properly with compressed air and CFRP sheet/plate was attached on 3 sides on the prism in turn. In two of the systems, primer layer was allowed to harden for a day before attaching the CFRP sheet. As it was difficult to control the thickness of the resin layer, the quantity of the resin was measured and applied based on surface area coverage recommendation provided by the manufacturers. On each surface of the concrete prism, CFRP was attached at two different areas to perform both shear and pull-off bond test as shown in Fig. 4 (a). The upper part of the concrete prism was used for the shear bond test; whereas the lower part was used for the pull-off test. After attaching the CFRP on all three sides, specimens were put in the laboratory conditions for more than one month as a curing period before giving any kind of environmental exposure. The final set of all 6 specimen types are shown in Fig. 4 (b). The naming system used for the CFRPs, epoxy resins and all the specimens are presented in Table 2.

## Exposure and testing conditions

The specimens were either kept at an ambient condition inside the laboratory until the test which is referred as 0 month (non-immersion case) or completely submerged in water tank maintained at a constant temperature of 20 °C for the maximum period of 18 months. The reason behind selecting only a single temperature range was mainly based on results of the elevated temperature test. When the six systems were tested at 20 °C, 40 °C and 50 °C, none of the cases showed any form of reductions in the bond strength (Shrestha, 2015). In addition, to investigate the sole effect of moisture conditions, it was necessary to eliminate the changes in the properties of the materials and the bonds due to temperature. Therefore, by selecting the room temperature well below the glass transition temperature of the resins, it eliminates any possibility of altering the property due to temperature. As for the testing, a set of specimens was taken out from the water in every 3 months interval and quickly taken into the temporary environmental chamber built around the testing machine in order to keep the exposure and testing conditions similar. Both the shear bond test and resin tensile test were conducted inside the environmental chamber which could maintain the desired temperature and humidity. The schematic of the testing arrangement of the shear specimen inside the controlled chamber along with the specimen during the test is shown in Fig. 5. Throughout the test period, the temperature of 20±3 ˚C and humidity over 85% was maintained in order to prevent the loss of moisture from the specimens. As for the direct pull-off test, shown in Fig. 6, no such arrangement was made to control the temperature and humidity of the testing condition as the setting and testing period was very short which could be assumed to have negligible effect. At the end of 18 months immersion, a set of specimens were removed from the water and transferred into a chamber for the purpose of drying. The specimens were kept inside the chamber for 4 days at a constant temperature of 28 ˚C. The specimens were assumed to have dried when the change in weight within a day was less than 0.1%. The main reason for this is to investigate the reversible or irreversible effects caused due to immersion in water. Three specimens were tested for each exposure condition in order to ensure the reliability of the obtained results.

## Test Procedures and Instrumentation

Tensile test of the resin specimens and the single lap shear bond tests were conducted in a universal testing machine (UTM) at the loading rate of 2 mm/min and 0.2 mm/min respectively. As for the setup of the bond specimens, the CFRP-concrete bond interface was aligned with the centerline of the upper loading grip in order to ensure the pure shear stresses at the interface.  The specimens were fixed on the testing machine by four long bolts, inserted through the hollow PVC pipes. On the top of the specimen, a steel plate was placed to ensure reaction during the loading. The arrangements are shown clearly in the Fig. 5. CFRP The pull-off test was conducted in accordance to JSCE (2001) with the dolly size of 40x40 mm. A portable adhesion testing device of maximum capacity of 10 kN was used. Loading was applied in the rate of 5-10 kN per minute manually.

# RESULTS AND DISCUSSION

## Moisture absorption by epoxy resin specimens and its effect on the mechanical properties

To address the moisture effect on the CFRP-concrete bond properties, it is crucial to know the effect on the constituent material properties. In this regard, it is necessary to understand the moisture transportation, absorption characteristics and its influence in the mechanical behavior of the epoxy resins. Therefore, water absorption was monitored in the epoxy samples at different interval of time using gravimetric method. The exponential rising curve showed good fitting to represent the relationship between water absorption and the exposure duration in months as shown in Fig. 7. The regression coefficient in all the cases were greater than 0.98.  The diffusion rate of water and the absorption capacities were found to be varied greatly based on the resin type. However, even after 18 months of water immersion, none of the resin specimens showed fully saturated condition. The maximum water absorbed by the resins were in the range of 0.71% to 2.65% after 18 months of immersion in water. Five of the cases (TR-A, TR-B, TP-B, TR-C, TR-D) showed similar water absorption behavior. On the other hand, the resin specimens, TP-A, TR-E and TR-F, showed relatively lower water diffusion rate and the water absorption. TR-E and TR-F contain higher filler materials (silica, calcium carbonate etc.) which could have also contributed towards lowering the free volume inside the resin resulting in the lower absorption. Tu and Kruger (1996) reported similar absorption nature by the higher filled adhesive.

Previous researchers have reported that the water absorption by the epoxy resin in the range between 1 to 7% by weight based on their formulations (Soles, et al., 1998). There are several existing theories on the factors contributing to the moisture absorption. Struik (1977) proposed that the quantity of water absorbed is dependent on the amount of free volume which depends on the molecular packing and is affected by the crosslinking density and the physical aging. In contrast, Li, et al. (2009) proposed that the free volume is not a decisive factor but the polarity of the resin system plays a key role. Soles, et al. (1998) argued that the polarity is the significant factor in determining the ultimate moisture uptake, however, the free volume fraction also influences the moisture uptake. The above discussion may explain the possible reasons of large variation in the moisture absorption capacities shown by the different resin specimens.

In Fig. 8, the relationship between average tensile strength and water absorption shows two distinct trends. Except in two of the cases (TR-B and TR-C), the increase in the moisture absorption resulted in reduction of the tensile strength. However, depending on the resin type, the degree of such effect varied. The highest reduction in tensile strength occurred in the resin TR-F with an average reduction of around 38% after exposure, but, the ultimate water absorption was only 0.71%. Whereas, those with the water absorption of over 2% showed reduction in between 11% to 22%. In two of the cases, TR-B and TR-C, there was no effect despite the water absorption of around 2%. Therefore, all the above results indicate that the durability of the resins are highly dependent on the materials and the amount of water absorption alone cannot be used as an indicator to judge or predict the effects caused by itself.

Figure 9 shows the relationship between average tensile strength of the resin and the exposure duration. The duration of the moisture exposure resulted in reduction of the tensile strength of the resins expect in the case of TR-B and TR-C. Plasticization, hydrolysis, cracking and crazing are few of the existing reasons for such moisture related deteriorations in the properties of the resins, however, there is no proper explanation yet for better resistance shown by two of the resin types. In contrast to the tensile strength behavior, the tensile modulus was not significantly affected by the exposure duration as shown in Fig. 10.

Figure 11 and Fig. 12 show the comparison of the tensile strength and modulus of the resin specimens respectively tested under wet and dry condition after 18 months of exposure. The results show that drying of the resins after 18 months of immersion in water does not recover the initial mechanical properties, indicating that the exposure due to the moisture conditioning caused some irreversible effect in the resin properties. These irreversible effects could be due to loss of crosslinking density and permanent swelling of the resins (Tuakta and Büyüköztürk, 2011).

## Effect of moisture on the shear bond failure modes

Based on the observation of the failure surfaces after the shear test, the failure modes can be categorized into 3 groups. Cohesion failure at the concrete layer (C) (Fig. 13a), mixed failure (M) (Fig. 13b) and finally, the interface failure between concrete and resin layer (I) (Fig. 13c). Among above three, concrete cohesion failure is the common mode of failure under normal environmental condition. This failure mode was common in specimens SB-A, SB-E and SB-F, indicating good adhesion bond between the CFRP and concrete. As for the specimens SB-

B and SB-D, the failures were usually of mixed type defined as the partial failure in concrete cohesion and resin-concrete interface adhesion failure. The failure percentage in concrete to the resin-concrete interface varied even within the similar exposure condition, but, no distinction is made between such cases and generalized as a mixed failure mode. The last failure mode was the adhesion failure at the interface between resin and concrete. This failure mode is the least desired implying either insufficient surface preparation or the weak adhesion bonding of the resin with the concrete. The latter could be the reason  in specimen SB-C, as similar degree of surface preparation was done in all the systems.

Transition of failure mode from the concrete cohesion to either mixed or interfacial failure was observed as an effect of moisture. Most of the specimens within SB-A, SB-B, SB-E and SB-F showed such transitions after the exposure. Likewise, the mixed failure mode before the exposure either retained the same or changed to interfacial failure as in cases of SB-B and SB-D. Lastly, the interfacial failure cases observed in SB-C, retained the same failure modes irrespective of the exposure and its duration. Even drying the specimens after 18 months of immersion did not affect the failure modes. Most of the results were comparable with the wet cases. The distinction of all the failure modes after different exposure durations are summarized in Table 3.

Analysis of the failure modes indicate that among four different wet-layup systems, the cases with primer layer (SB-A and SB-B) showed relatively better adhesion bond with the concrete. In both the cases, the greater percentage of failures occurred in concrete layer near the interface before and after the exposure. In addition to this, reduction in the shear bond strength after the exposure was comparatively lower than other wet-layup systems without the primer layer. The results indicate that the primer could be a beneficial layer in case of durability against moisture related effects. However, comparing the separate systems may not be fair enough, as difference in material properties could affect the result. In future, it may be necessary to conduct some further similar exposure tests without applying the primer layer to make a direct comparison within the system in order to clarify the role of primer in case of moisture related durability issues. But, in a separate study (Shrestha, et al., 2014), the authors confirmed the effect of primer and surface preparation on the CFRP-concrete bond interface without any form of environmental exposure. In such normal condition, the results revealed no additional benefit of applying primer layer in terms of shear bond strength and direct pull-off strength.

## Moisture effect on the shear bond strength

Figure 14 shows the variation of the average shear bond strength with the exposure duration. Initially, in the first 3 months of exposure, the moisture seems to show significant reduction in the bond strength after which it was retained in most of the cases in extended exposure duration. From the figure, it is also evident that the bond strength increased significantly in case of SB-F system after 3 months of immersion till the 9 months and then remained almost constant till the 18 months. As for SB-E system, the bond strength remained fairly unchanged until 9 months followed by a small increment in 12 months and then remained almost constant until the 18 months. For rest of the cases, it is rather difficult to see the clear trend from the figure due to overlapping of data points. Therefore, Fig. 15 shows the shows the relationship between average bond strength at each exposure duration normalized by the average bond strength for non-immersion case. The average value was calculate based on the results 3 specimens tested for each exposure condition. Based on the changes in the average bond strength with the exposure duration, results could be categorized into 3 groups. The systems such as SB-A, SB-B and SB-E with less than 5% reduction in the average bond strength between non-immersion and immersion is grouped in the first category. As for the duration of immersion period, there is no strong correlation between the change in the bond strength and the exposure duration. The failure modes for these sets remained either as concrete cohesion or the mixed mode after such exposure.

The second group includes SB-F type specimen, the CFRP plate bonded to the concrete, which shows significant gain in bond strength after exposure. Compared to the non-immersion case, the average bond strength increment of 34% was found after immersion case implying some positive effects of water on the bond properties. This increment in the bond strength was mainly started after 3 months of exposure duration. This is in contrary to some of the previous reported results in which the CFRP plates bonded to concrete specimens performed poorer than the sheets (Dolan, et al., 2009, Grace and Singh, 2005). Despite the better properties of CFRP plate compared to the sheet, the main reason for such poorer performance is attributed to durability issues of the epoxy adhesives used in such systems. Even in the present case, the epoxy resin used for this system showed significant degradation in the mechanical property, but that effect was not reflected in the ultimate bond strength as the failure occurred at concrete cohesion layer. This indicates that the shear strength of the degraded resin is still higher than that of the concrete but this still does not explain the reason for enhancement in the bond strength. Similar increase in bond strength was also reported by Al-Tamimi, et al. (2014) in the case of CFRP plate. The main reason for such increase in strength was attributed to the enhancement of the polymer strength due to increase in temperature during the exposure. In contrast, the temperature in the current study was always close to 20 °C from initial curing of specimens to the exposure condition and then the testing temperature, so such post-curing effect is highly unlikely to be the reason for increase in bond strength. Further, the specimens were cured for more than a month before exposing them into water, which was considered as a sufficient period for proper curing of the resins. There are some other possibilities as well which could justify such improvement in the shear bond strength after exposure. The first one could be due to increment in the concrete strength due to better curing conditions provided by curing under water but, the results obtained from the concrete compression test, as presented in Fig. 16, clearly showed that the compression strength remained fairly constant throughout the exposure duration implying no enhancement in concrete properties. In addition, despite of being the same batch of concrete with similar failures in concrete cohesion, specimens such as SB-A and SB-B did not show any improvement in the bond strength. Therefore, these evidences totally eliminate any chances for concrete to be the reason for strength enhancement after exposure. Other remaining possibilities for improvement could be either due to increase in the stiffness of CFRP or the softening of the resins due to exposure. From the measurements of the strains at the unbonded region during the shear bond test confirms that the stiffness of CFRP did not vary even after the exposure. As for the resin, the tensile modulus was slightly lower but considering the scatter at different durations, it is insignificant. Therefore, the improvement in the load transfer mechanism between the CFRP and concrete due to exposure is still unknown and needs further investigation.

The shear bond strength in the third category of the specimens SB-C and SB-D was significantly reduced by the exposure. The average losses in bond strength after the exposure are 25% and 16% respectively. Significant reductions could be observed in just 3 months of exposure duration and remained almost in the same range throughout the exposure duration. This indicates that the effect of moisture on the bond strength can be reflected in a very short duration of time. The failure modes are also distinct in these two systems. In contrast to the remaining systems, which mostly failed by concrete cohesion, specimens SB-C and SB-D showed failure at the interface between concrete and resin layer. Despite the similar degree of surface preparation, the failures at the interface even before the exposure imply weaker adhesion between them. At the interface between concrete and resin, mechanical and chemical bond are two key mechanisms which govern the bond action (Shrestha, et al., 2014). The reduction in bond strengths after the exposure indicates that either one or both of the mechanisms are affected by the presence of water. Water at the interface can reduce the mechanical interlocking action or destroys the chemical bonds between resin-concrete at the interface. These two factors may have contributed towards the reduction of the bond strength. The degradation of such mechanical interlocking capacity at the epoxy-concrete interface due to absorbed water was also reported by Dolan, et al. (2009). In summary, the effect of water is prominent in cases when the surface roughness is not sufficient enough or the adhesion bonds between resin and concrete is not strong enough, resulting in the adhesion failure at the interface. In such a situation, significant loss in bond strength could occur after immersion. Similar result was also observed by Shrestha et al. (Shrestha, et al., 2014) when CFRP bonded to high strength substrate concrete failed at the interface after immersion in water. A year of exposure in water resulted in 30% and 32% reduction in average bond strength respectively for two types of specimen with different primer layer. In the same research, such deterioration of bond strength was not observed for normal strength concrete substrate despite the use of same CFRP composites and the exposure condition. The failure surfaces in those cases were always mixed type. These evidences and discussions could clearly demonstrate that the interfacial failure of bond is the most severe case at which the water deteriorates the bond strength significantly. It also highlights the necessity of proper surface preparation of the substrate concrete and the use of appropriate epoxy resin with higher adhesion strength to ensure stronger bond at the interface than the adjacent layers and remain durable against the moisture environments.

The effect of wet and dry testing conditions were also examined on the shear bond strength after 18 months of immersion in water as shown in Fig. 17. About less than 5% recovery of average bond strength was found in specimens SB-C and SB-F, whereas the recovery was over 10% in case of specimens SB-A and SB-B but no such effect was observed in SB-D case. The results of specimen SB-E was not included due to some problems associated with the specimen during preparation process. In conclusion, even though slight recovery of bond strength was noticed in some cases after drying, it could not restore back to the original state indicating that the deteriorations due to water causes irreversible effect on the bond properties.

## Moisture effect on the tensile bond strength

The pull-off test method is a simple method to evaluate the quality of tensile bond in the field. This method was used to determine the relative performances of CFRP-concrete bond after different moisture exposure conditions shown in Fig. 18. Despite the large variation in the results, reduction in the average tensile bond strength is evident in most of the cases as a result of the exposure. In few of the cases, the value of the tensile bond strength after the exposure was even lower than the minimum pull-off strength of 1.4 MPa which is recommended by ACI-440.2R-08 (2008). Except system TB-B, the average reduction in the tensile bond strength varied from 19% to 41% in 18 months period after the exposure. Table 4 shows the ratio of the average tensile bond strength at different duration, normalized by the non-immersion (0 month) case. Some of the other researchers have also observed such adverse effects due to moisture exposure conditions resulting in reductions in tensile bond strengths , but, in most cases such reductions were accompanied by transition of failure surfaces from concrete to mixed or complete interfacial failures (Au and Büyüköztürk, 2006, Benzarti, et al., 2011, Dai, et al., 2010, Karbhari and Ghosh, 2009). In contrast to the above behavior, the present study didn’t observe such transition of failure modes after the exposure despite some reductions in the tensile bond strengths. The concrete cohesion failure mode remained unchanged in majority of the cases even after the exposure. Comparison of a typical failure mode before and after exposure is shown in Fig. 19. Similar kind of observation was also reported by Nishizaki and Kato (2011), in which the authors suggested that such reductions without the transition of failure modes maybe due to change in behavior of concrete properties rather than the degradation of the bond properties. However, no information on the durability of the concrete properties were provided. Nonetheless, in the current study, the concrete compression behavior was not affected by the exposure duration (Fig. 16), so based on that, it can be assumed that the tensile behavior may not have affected as well, implying the reductions could have caused by environmental degradation of the resins.

Figure 20 shows tensile bond strength comparison tested under wet and dry condition after 18 months of exposure in water. Similar to the shear bond behavior, drying process helped recovery of the tensile bond strength, but was not able to retain back the original state. Only in the case of specimen TB-B, the resulting strength was higher than the original strength. Even in the failure modes, no distinction could be made between those conditions as most of them failed in concrete.

In summary, the effect of exposure in water caused significant reductions in tensile bond strengths which could be partially recovered by drying process. The distinction between durability performances in different CFRP systems cannot be made as the failure were governed by the concrete cohesion strength. Despite some reductions in the bond strength, the good adhesion was still retained between CFRP composite and the concrete substrate even after the exposure. Nevertheless, the tensile bond strengths obtained here can just be used as indicative values to compare the relative changes in the performances over different environmental conditions.

## CONCLUSIONS

The durability of CFRP-concrete bond interfaces for 6 commercially available CFRP and epoxy resin systems were evaluated with single lap shear bond test and direct pull-off test together with tensile test of the resins. Based on the observed results of immersion for the period of 18 months, following conclusions can be drawn:

1. The water absorption capacities of the resin varied greatly from 0.71% to 2.65% after 18 months of immersion in water at 20°C. The water absorption by the resin proved to be harmful affecting the tensile strength in most of the cases but no strong relationship was found between amount of moisture absorption and the tensile strength. In contrast to the strength behavior, the modulus was not much affected by such exposure.

2. In response to moisture exposure, the shear bond behavior showed either reduction or increment in the bond strength depending on the CFRP systems. After the exposure, less than 5% change in bond strength was observed for types SB-A, SB-B and SB-E, whereas, such reductions increased to 16% and 25% respectively in SB-C and SB-D types. In contrast, there was an increase in average bond strength of about 34% in case of SB-F type. It can also be concluded that longer duration of exposure does not necessarily mean greater effect. At the later stages of exposure duration, the bond strength remained almost constant.

3. As for the failure modes in shear bond tests, three typical failure modes were observed, which are concrete cohesion failure, partial concrete cohesion and resin-concrete interface failure and lastly adhesion failure between resin and concrete. As an effect of water immersion, transition of failure modes occurred from concrete cohesion to mixed mode or interface failure but significant reductions in bond strength were observed only in the cases of complete interface failures. This emphasizes the importance of proper surface preparation required in substrate

concrete and use of the resin with good adhesion bond strength with concrete to ensure greater durability of CFRP-concrete bond against moisture related effects.

4. Tensile bond strengths obtained from direct pull-off tests were reduced significantly in most of the cases after exposure, but the failure modes, which were concrete cohesion failures remained unchanged. This fact suggests that there are some harmful effects of water immersion in tensile bond properties, however no reasonable explanation can be made for the reason of strength reduction.

5. A set of specimens was also tested in dry condition after 18 months of exposure in water to evaluate reversible and irreversible effects. In general, the results revealed that the mechanical properties of the resins were further deteriorated after drying, in contrast, both the shear and tensile bond strengths were partially recovered but not restored to the original strength. These results indicate that the effects caused due to exposure in moisture are mostly irreversible.

Based on the above conclusions, it is clear that moisture condition is one of the key environmental durability issues which could prematurely degrade the bond between the FRP and the concrete. Therefore, such consideration should be made during the design stage to ensure safety and longevity of the structure. While the authors will propose the relevant constitutive laws for the interfaces in case of moisture conditions in the next paper, the present paper would serve to clarify some of the key issues related to the moisture effect on the bond properties. The bond values obtained as the result of exposure could be utilized to calculate the reduction factor. Such factor could be used as an additional reduction coefficient in the member resistance to consider the bond degradation between FRP and concrete due to the moisture dominant environment condition in the field applications. However, this factor should be limited only to the bond critical applications for strengthening with the wet-layup CFRP system under normal temperature range of 20 ˚C.

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**Table 1.** Properties of the FRPs and the epoxy resins

| Description | System-A | System-B | System-C | System-D | System-E | System-F |
|---|---|---|---|---|---|---|
| **Type** | Carbon fiber sheet | Carbon fiber sheet | Carbon fiber sheet | Carbon fiber sheet | Carbon fiber strand sheet | Carbon fiber plate |
| **Fiber content** | 200 g/m$^2$ | 200 g/m$^2$ | 393 g/m$^2$ | 200 g/m$^2$ | 600 g/m$^2$ | >68% |
| **Thickness** | 0.111 mm | 0.111 mm | 0.218 mm | 0.176 mm | 0.333 mm | 1.4 mm |
| **Width of the plate** | - | - | - | - | - | 50 mm |
| **Strength (MPa)** | 3400 | 3400 | 3790 | 3800 | 3400 | 3200 |
| **Young's modulus (GPa)** | 230 | 230 | 230 | 240 | 245 | 210 |

| Description | Epoxy-A | | Epoxy-B | | Epoxy-C | Epoxy-D | Epoxy-E | Epoxy-F |
|---|---|---|---|---|---|---|---|---|
| **Type** | matrix | primer | impregnating resin | primer | matrix | matrix | adhesive paste | adhesive paste |
| **Mixing ratio (B:H)** | 2:1 | 2:1 | 4:1 | 4:1 | 100:34.5 | 2:1 | 4:1 | 3:1 |
| **Main composition (Base)** | Bisphenol A type epoxy resin | | | | Modified epoxy resin | Bisphenol A type epoxy resin | | |
| **Main composition (Hardener)** | Modified aliphatic polyamine | | | | Polyoxypropylenediamine (aliphatic amine), Polyetheramine (aliphatic amine) | blend of cycloaliphatic, isophoronediamine, Triethylenetetramine (aliphatic amine) | Modified aliphatic polyamine | Trimethyl hexamethylene diamine (aliphatic amine) |
| **Tensile strength (MPa)** | 56.74 | 64.02 | 39.66 | 52.62 | 56.50 | 53.87 | 55.96 | 32.55 |
| **Young's modulus (GPa)** | 3.10 | 3.30 | 3.90 | 3.40 | 3.80 | 2.73 | 5.63 | 10.70 |
| **Poisson's ratio** | 0.35 | 0.38 | 0.34 | 0.43 | 0.33 | 0.37 | 0.38 | 0.29 |
| **Glass transition temperature (˚C)** | 48.7 | 45.9 | 49.5 | 55 | 54.3 | 53.6 | 49.3 | 56.5 |

Except the tensile strength, Young's modulus, Poisson's ratio and the Glass transition temperature of the resins, all other information are provided by the manufacturers

**Table 2.** Naming scheme for the specimens

| Composite System | Epoxy | Tensile resin specimens | | Shear bond specimens | Tensile bond specimens |
|---|---|---|---|---|---|
| | | Matrix/ Adhesive | Primer | | |
| A | Epoxy-A | TR-A | TP-A | SB-A | TB-A |
| B | Epoxy-B | TR-B | TP-B | SB-B | TB-B |
| C | Epoxy-C | TR-C | - | SB-C | TB-C |
| D | Epoxy-D | TR-D | - | SB-D | TB-D |
| E | Epoxy-E | TR-E | - | SB-E | TB-E |
| F | Epoxy-F | TR-F | - | SB-F | TB-F |
| 3 specimens were tested for each case | | | | | |

**Table 3.** Summary of the failure modes in shear bond test

| Exposure duration (Months) | Testing condition | Failure modes | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SB-A | | | SB-B | | | SB-C | | | SB-D | | | SB-E | | | SB-F | | |
| | | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| 0 | Wet | C | C | C | C | M | C | I | I | I | M | M | M | C | C | C | C | C | C |
| 3 | Wet | C | C | C | M | M | C | I | I | I | I | I | I | C | C | C | M | I | C |
| 6 | Wet | C | M | C | C | M | C | I | I | I | I | I | I | C | C | C | M | M | M |
| 9 | Wet | C | C | C | M | I | M | I | I | I | I | I | I | C | C | C | C | M | M |
| 12 | Wet | M | M | C | C | M | I | I | I | I | I | I | I | C | C | M | C | M | M |
| 15 | Wet | C | M | M | M | I | M | I | I | I | I | I | I | M | C | C | M | M | M |
| 18 | Wet | C | M | M | M | M | M | I | I | I | I | I | I | M | M | M | M | M | C |
| 18 | Dry | M | M | M | M | M | M | I | I | I | I | I | I | - | - | - | M | M | M |

C=Concrete cohesion; M=Partial concrete cohesion and resin-concrete interface; I=Resin-concrete interface

**Table 4.** Summary of the average tensile bond strength normalized by the non-immersion (0 month) case

| Exposure duration (Months) | Testing condition | Normalized value of average tensile bond strengths by 0 month | | | | | |
|---|---|---|---|---|---|---|---|
| | | **TB-A** | **TB-B** | **TB-C** | **TB-D** | **TB-E** | **TB-F** |
| 0 | Wet | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 3 | Wet | 0.61 | 1.19 | 0.66 | 0.81 | 0.59 | 0.51 |
| 6 | Wet | 0.44 | 1.27 | 0.88 | 0.84 | 0.60 | 0.59 |
| 9 | Wet | 0.44 | 1.59 | 0.58 | 0.97 | 0.71 | 0.52 |
| 12 | Wet | 0.82 | 1.25 | 0.97 | 0.90 | 0.75 | 0.68 |
| 15 | Wet | 0.96 | 1.69 | 1.21 | 0.81 | 1.02 | 0.75 |
| 18 | Wet | 0.52 | 0.85 | 0.56 | 0.33 | 0.89 | 0.51 |
| 18 | Dry | 0.72 | 1.49 | 0.66 | 0.74 | - | 0.61 |

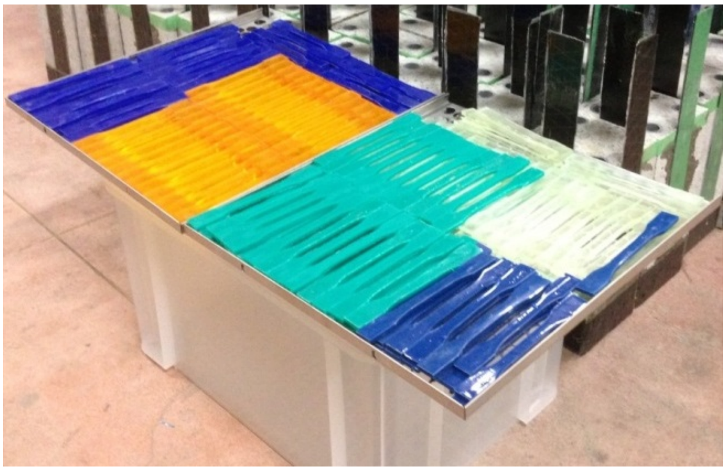


**Fig. 1.** Epoxy resin specimens for the tensile test

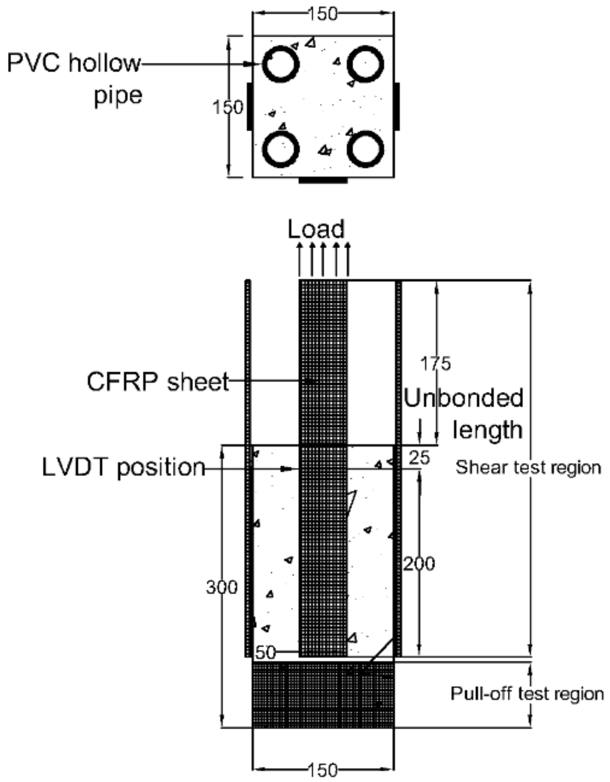



**Fig. 2.** Details of bond specimen (unit: mm) for single lap shear test

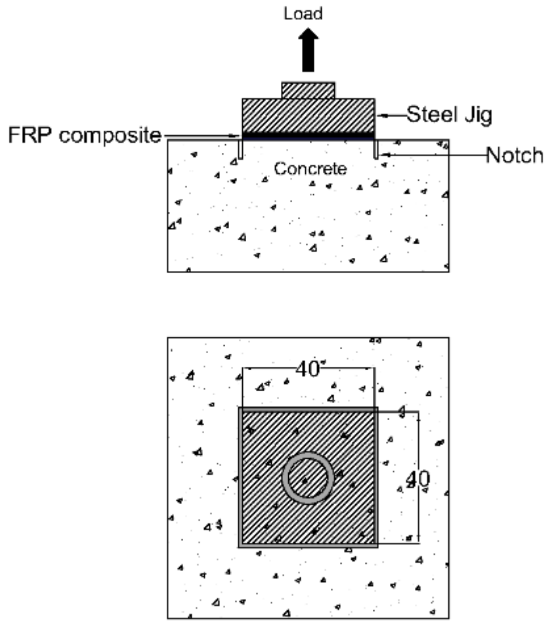
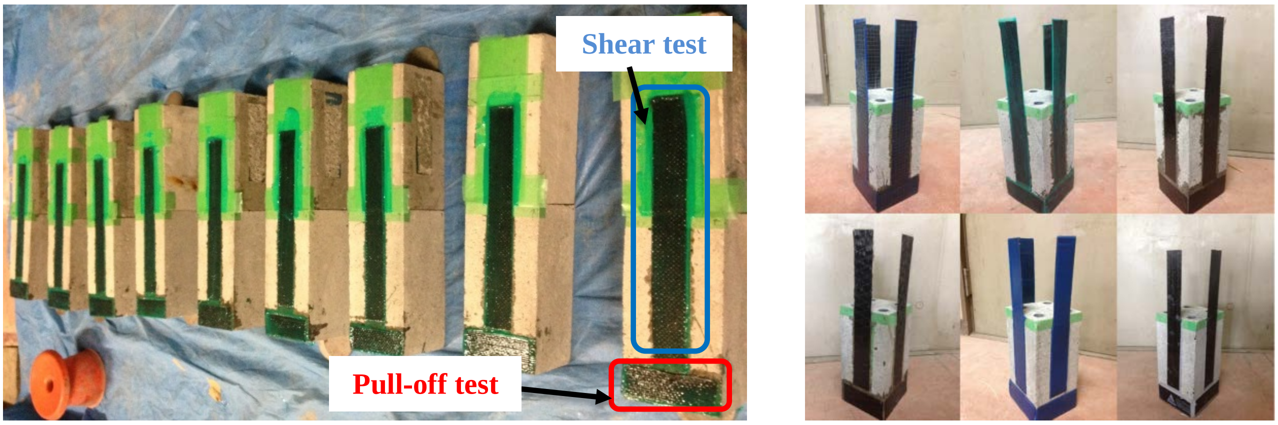
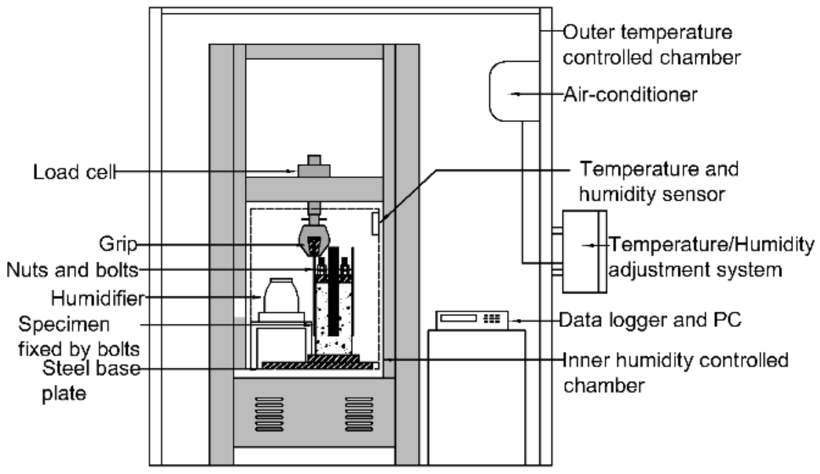



**Fig. 3.** Details of direct pull-off test specimen (unit: mm)

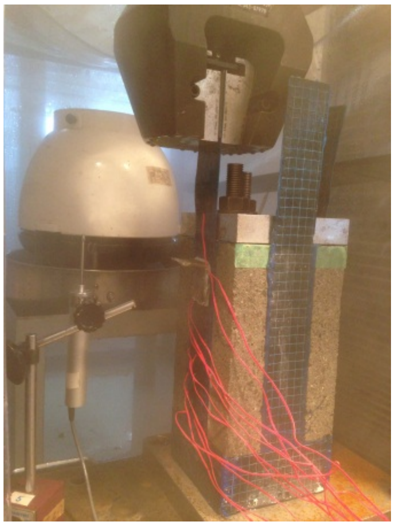



(a) (b)

**Fig. 4.** (a) Preparation of the bond specimens; (b) Sample specimen for each FRP system




(a)



(b)

**Fig. 5.** (a) Test arrangement schematic for the bond specimen inside the environmental testing chamber ; (b) Specimen during the test inside the chamber

**Fig. 6.** Direct pull-off test setup

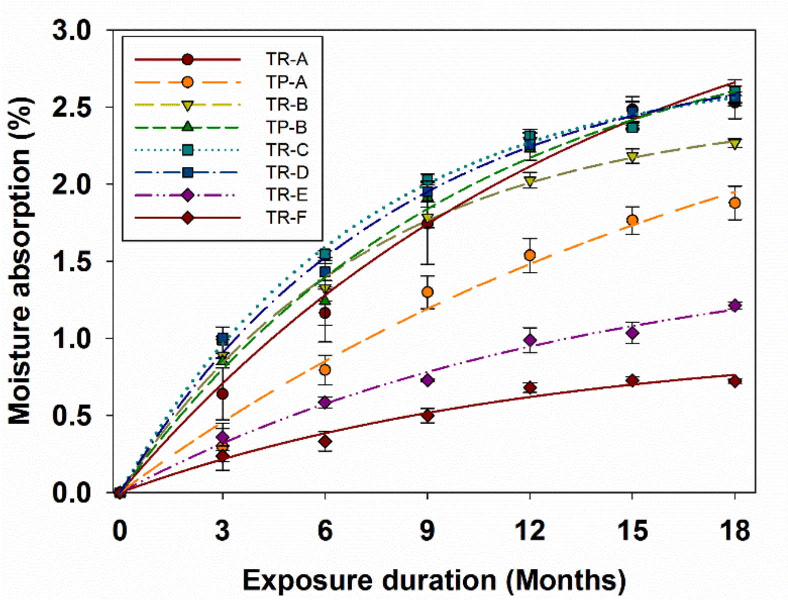



**Fig. 7.** Moisture absorption by epoxy resin specimens

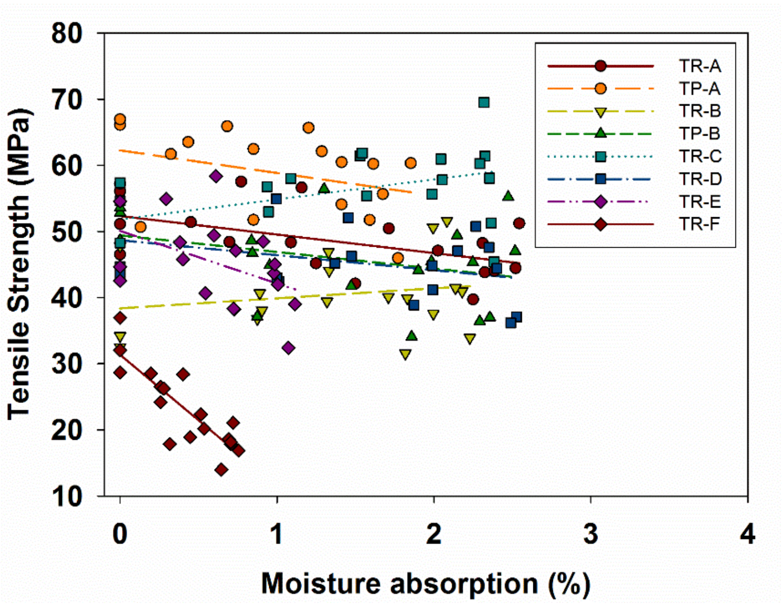



**Fig. 8.** Relationship between tensile strength with the moisture absorption by the resins

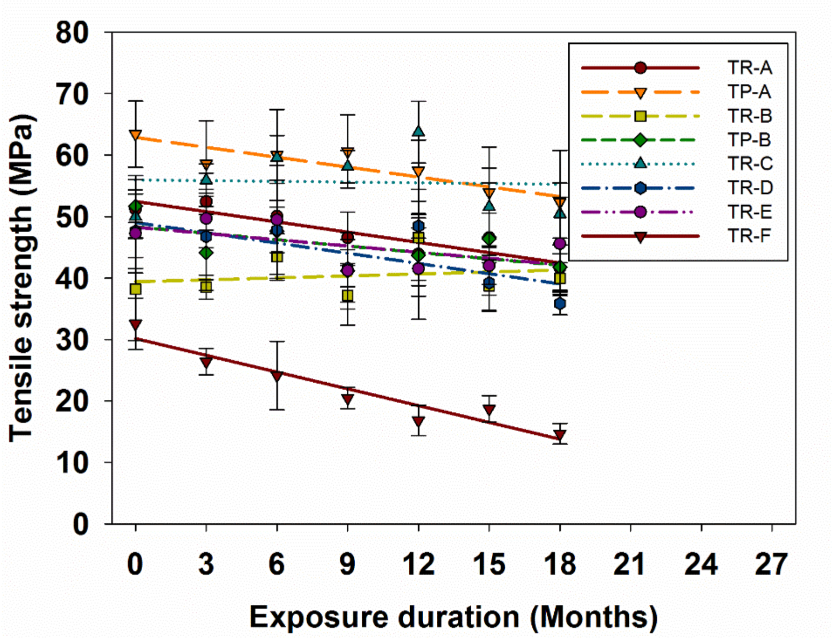



**Fig. 9.** Exposure duration effect on the tensile strength of the resins

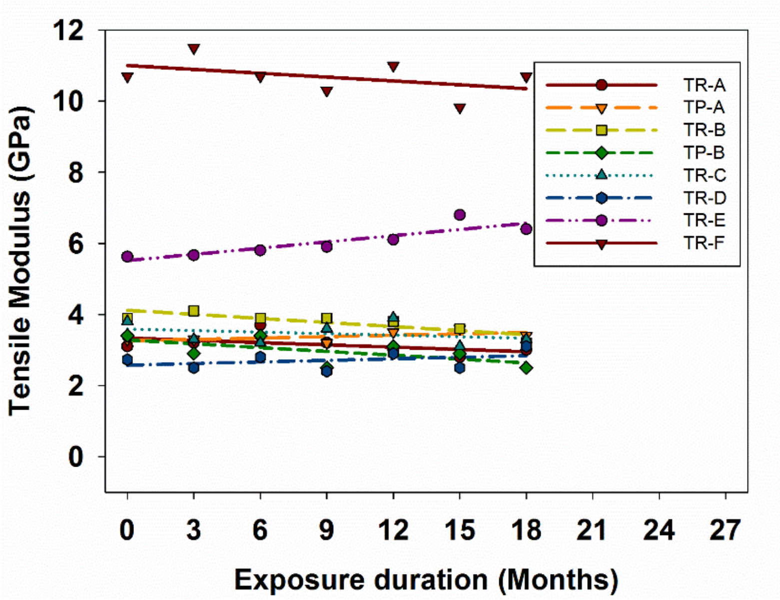



**Fig. 10.** Effect of the exposure duration on the tensile modulus of the resins

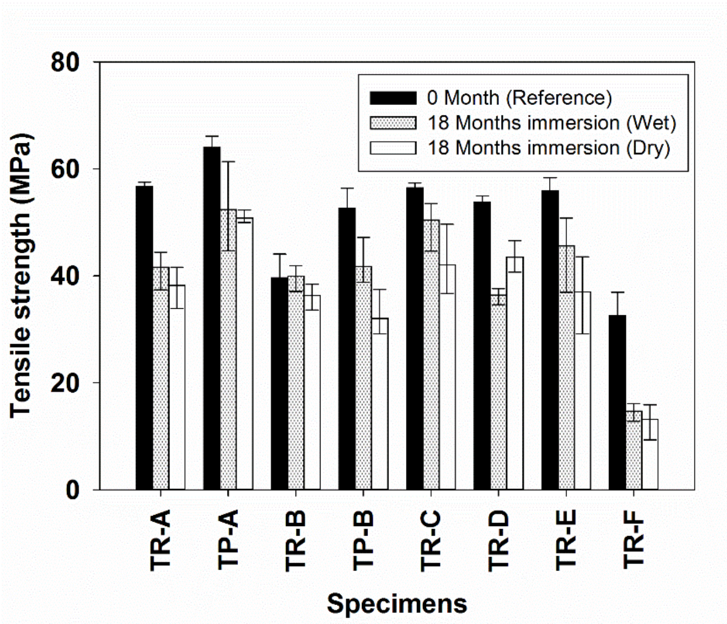



**Fig. 11.** The effect of testing condition (wet/dry) on the tensile strength of the resins after 18 months of immersion in water

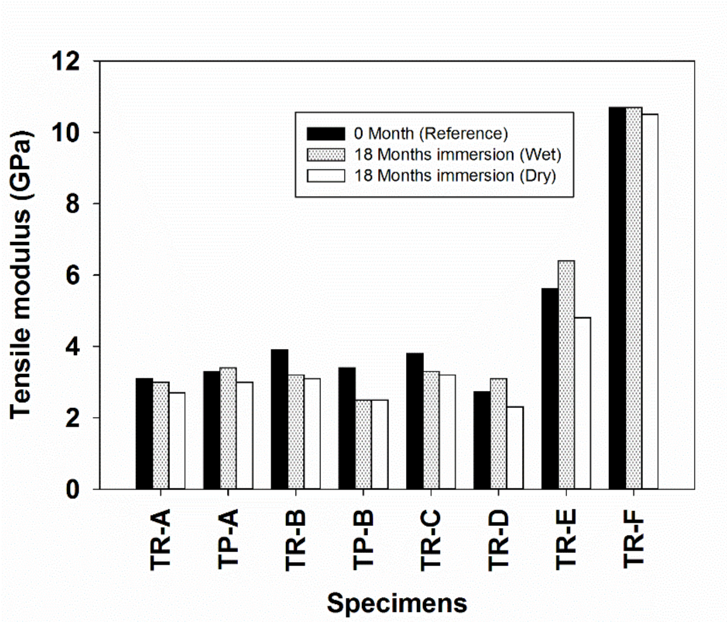
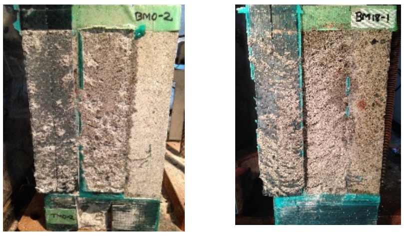


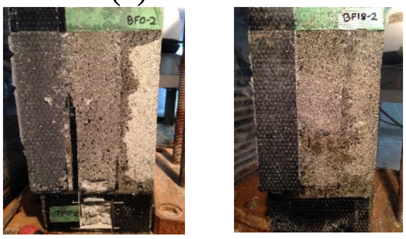

**Fig. 12.** The effect of testing condition (wet/dry) on the tensile modulus of the resins after 18 months of immersion in water

**0 Month** **18 Months**

(a) Concrete cohesion failure



(b) Mixed failure



(c) Adhesion failure

**Fig. 13.** Comparison of three typical failure modes before and after 18 months of exposure

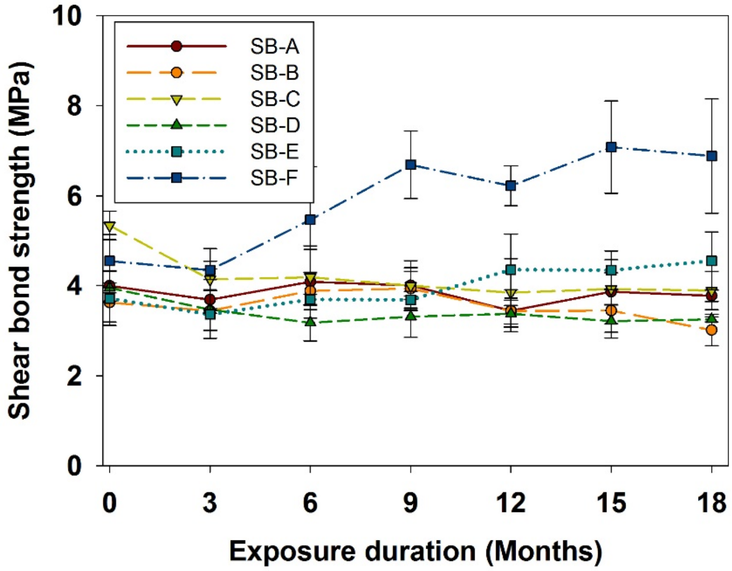



**Fig. 14.** Shear bond strength variation with the exposure duration

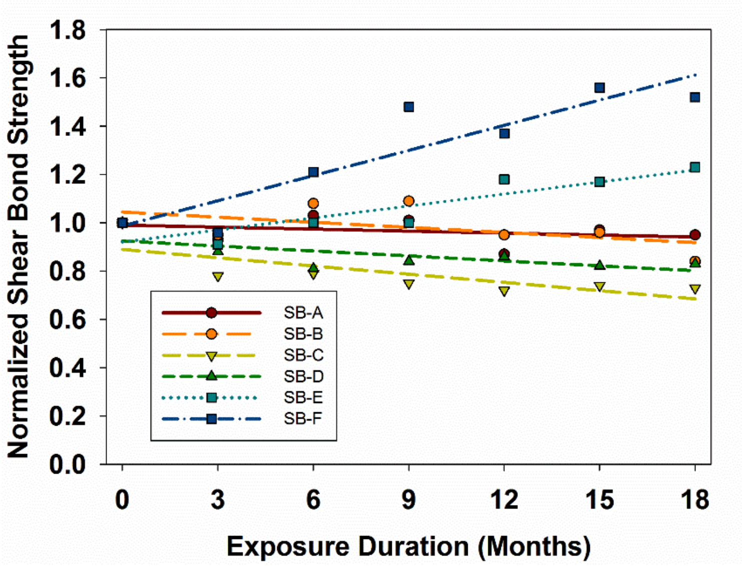



**Fig. 15.** Relationship between normalized shear bond strength and the exposure duration

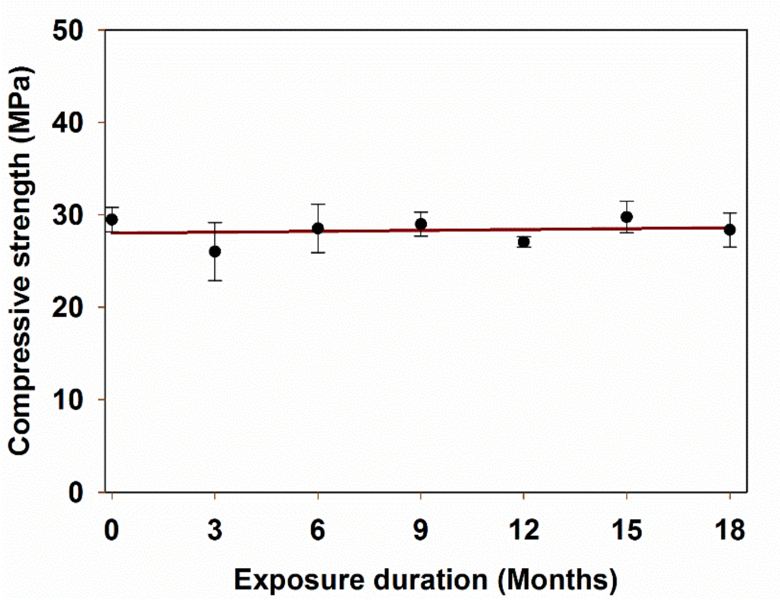



**Fig. 16.** Effects of exposure on the concrete compressive strength

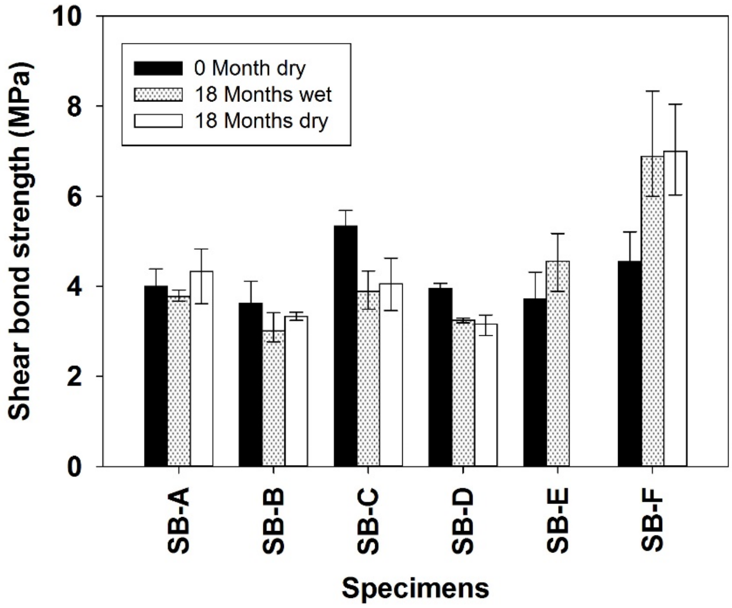



**Fig. 17.** Effect on shear bond strength after 18 months of immersion and different testing conditions (wet/dry)

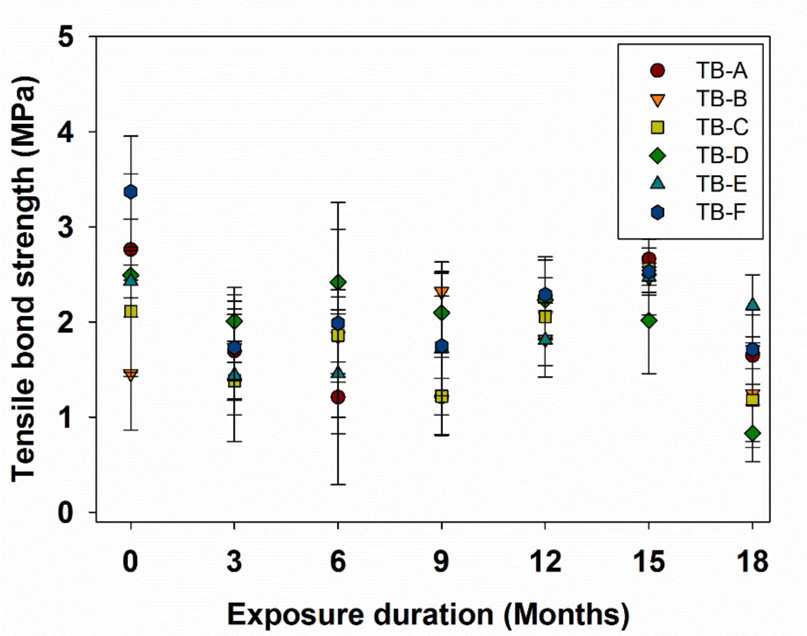



**Fig. 18.** Effect of tensile bond strength on the exposure duration

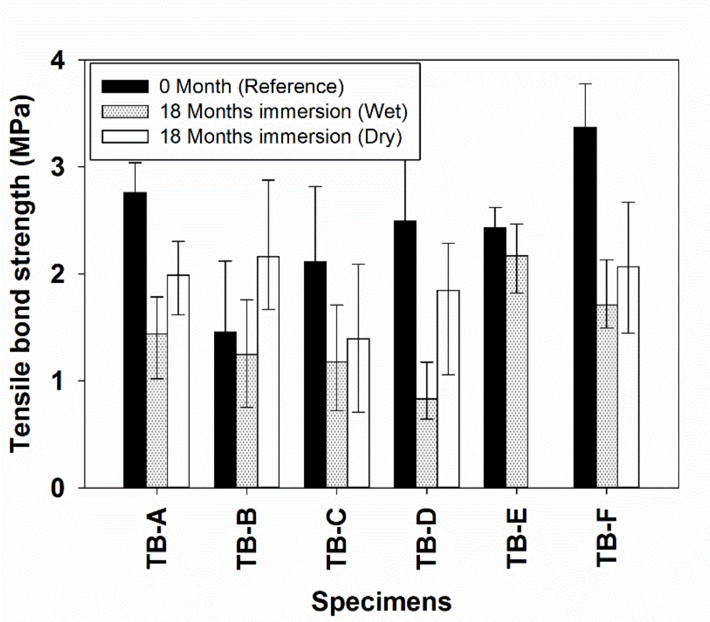



**Fig. 19.** The effect on tensile bond strength after 18 months of immersion and different testing condition (wet/dry)

**0 month** **18 months**


Complete failure at concrete layer

**Fig. 20.** Comparison of typical failure mode before and after 18 months of exposure